Choice Stepping Response and Transfer Times: Effects of Age, Fall Risk, and Secondary Tasks

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Background. Deterioration with age of physiological components of balance control increases fall risk. Avoiding a fall can also require higher level cognitive processing to select correct motor and stepping responses. Here we investigate how a competing cognitive task and an obstacle to stepping affect the initiation and execution phases of choice stepping reaction times in young and older people.

Methods. Three groups were studied: young persons (YOUNG: 23–40 years, n = 20), older persons with a low risk of falls (OLR: 75–86 years, n = 18), and older persons with a high risk of falls (OHR: 78–88 years, n = 22). Four conditions were examined: choice stepping, choice stepping + obstacle, choice stepping + working memory task, and choice stepping + working memory task + obstacle. Step response and transfer times were measured for each condition, in addition to hesitant stepping, contacts with the obstacle and errors made in the memory test.

Results. Older participant groups had significantly longer response and transfer times than the young group had, and the OHR group had significantly longer response and transfer times than the OLR group had. There was a significant Group × Secondary task interaction for response time (F2,215 = 12.6, p < .001). With the memory task, response time was minimally affected in the YOUNG (7% increase, p = .11) but was slowed significantly in the OLR fallers (42% increase, p < .001) and more so in the OHR fallers (48% increase, p < .001). The obstacle had a small but significant effect on response time (9.4%) and a larger effect on transfer time (43.3%), with no differences among the groups. Errors in stepping, performing the secondary task and contacting the obstacle increased with age and fall risk.

Conclusions. Compared with young people, older people, and more so those at risk of falling, have an impaired ability to initiate and execute quick, accurate voluntary steps, particularly in situations where attention is divided.

As people age they experience a decline in basic physiological functions required for stable standing and gait, including sensory acuity, lower limb strength, and reaction time. As a consequence, balance is threatened and the risk of falling increases (1,2). However, avoiding a fall depends not only on a person’s sensorimotor function and balance but also on cognitive processes that allow threats to balance to be perceived and appropriate corrective responses to be selected (3,4).

Dual or secondary task paradigms have been used to explore the attentional requirements of balance control (5). The premise is that when two tasks are performed simultaneously that require more than the total information processing capacity of a person, performance on either or both tasks deteriorates (6). Studies have shown that the attention required for balance control increases with the increased complexity of the balance task (7), the more complex nature of the cognitive task (8,9), increased age (5,10), and reduced balance abilities (5,11–15). It has also been suggested that as postural control requires considerable visuospatial processing, secondary tasks involving such processing may be particularly challenging when performing postural tasks (6,16).

Experimental paradigms that simulate situations such as tripping over an obstacle have also been used with individuals performing a secondary task. Chen and colleagues examined the effect of dividing attention on the ability of young versus older persons to step over obstacles (17). They found that dividing attention increased obstacle contact in both groups and to a greater extent in the older group. Performing a dual task while walking has been shown to increase swing time variability, a marker of fall risk, in older fallers but not in older nonfallers (18).

The above findings suggest that an experimental model incorporating a task that challenges balance combined with a visuospatial secondary task would be particularly appropriate for investigating the interaction between attention and balance among older people at low and high risk of falls. In a previous study we found that a test of choice stepping reaction time (CSRT) was able to discriminate between older people who had and had not fallen (19). In this test, participants must step from either leg onto targets that are illuminated randomly, and thus body weight and balance transfers are similar to the step responses required to avoid many falls, particularly those as a result of late visual detection of hazards and unanticipated changes in the gait path.

The present study examines the effects of performing a secondary visuospatial working memory task and negotiating a low obstacle in individuals of different ages and fall risk and examines whether differences in choice stepping time between these groups lie in the ability to select and initiate the correct motor output and/or in the time it takes to execute this action. We hypothesized that the visuospatial...
task would largely increase the central response time whereas the obstacle would affect the transfer time, and that these effects would be greater in the older participants, and particularly in those at increased fall risk.

**METHODS**

**Participants**

Twenty young persons (9 men, 11 women; mean age 29.1 years; standard deviation [SD] = 5.6) and 40 older persons (21 men, 19 women; mean age 81.2 years; SD = 3.2) participated in the study. The young participants (YOUNG) were a convenience sample of employees of the Prince of Wales Medical Research Institute and their friends and family. The older participants were living independently in the community and were recruited from a research database of individuals who had participated in previous studies (20). All participants were without cognitive impairment [i.e., a Short Portable Mental Status Questionnaire (SPMSQ) score <7 (21)], a history of significant neurological, musculoskeletal or cardiopulmonary disease, or visual impairment not correctable with glasses.

**Fall Risk Assessment**

Fall risk was determined with the short-form Physiological Profile Assessment (PPA) (22), which includes five validated measures of physiological functioning: visual contrast sensitivity, lower limb proprioception, quadriceps strength, reaction time, and postural sway. Visual contrast sensitivity was assessed using the Melbourne Edge Test (23). Proprioception was measured using a lower limb–matching task. Errors were recorded using a protractor inscribed on a vertical clear acrylic sheet (60 cm × 60 cm × 1 cm) placed between the legs. Quadriceps strength was measured isometrically in both legs, with the angles of the hip and knee at 90° with participants seated. The best of three trials was recorded and the scores were averaged across legs. Simple reaction time was measured using a light as the stimulus and a finger-press as the response. Postural sway was measured using a swaymeter that measured displacements of the body at the level of the waist. Testing was performed with participants standing on a foam rubber mat with eyes open (60 cm × 70 cm × 15 cm thick). In multivariate models, weighted contributions from these five variables provide a fall risk score that can predict those at risk of falling with 75% accuracy in community settings (22).

Based on a fall risk score of 1, the older participants were divided into two groups: 22 participants with high fall risk (OHR group) and 18 participants with low fall risk (OLR group). Normative data from prospective community studies (22) show that a fall risk score of ≥1 was associated with a 60.7% risk of multiple falling over 12 months, whereas a fall risk score <1 was associated with an 11.6% risk of multiple falling.

Demographic and health characteristics of the OLR and OHR groups are presented in Table 1. The groups did not differ significantly in terms of age, sex, medication use, or SPMSQ scores. In the previous year 54% of the OHR group reported falling, compared with 27% of the OLR group, a difference that approached statistical significance ($\chi^2 = 2.9, p = .088$).

**CSRT**

The CSRT device consisted of a low platform (80 cm × 80 cm × 3 cm high) that contained six plates (32 × 13 cm); two base plates on which the participant stood and four stepping plates that could be illuminated in a random order (Figure 1). Participants were instructed to step onto a plate as quickly as possible when it became illuminated, using the left foot only for the two left plates (front and side) and the right foot only for the two right plates. Participants stood with their feet 12 cm apart and in line with the two side plates. Stepping with their full foot onto the illuminated plate turned off the light. They then moved their foot back to the standing plate at their own pace. There was no requirement to hold the landing posture for a minimum time interval. Surface electromyography (EMG) was used to record activation responses in the medial gastrocnemius muscles of both legs and switches under each plate recorded the time of stepping events throughout a trial to within 1-millisecond accuracy.

The participants performed the choice stepping task under four conditions: choice stepping, choice stepping + obstacle, choice stepping + working memory task, and choice stepping + working memory task + obstacle. These conditions were administered in a random order with each comprising 20 trials with five illuminations per plate. Sufficient time was provided between trials for participants to reestablish their balance (usually between 5 and 10 seconds). Total testing time was approximately 30 minutes. To reduce fatigue, sitting breaks were provided if required.

Response time was recorded as the time from the plate illumination to the appearance of a significant EMG response prior to stepping in the appropriate leg. EMG onset latency was defined as the first normalized EMG burst exceeding the baseline level by 2 SD, and each trial was checked by visual inspection. Transfer time was recorded as the time from the appropriate EMG response to foot contact on the correct plate. From the lift-off events recorded by the stepping plates, incorrect start data were obtained. Thus, this method recorded “correct” response and transfer times with

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<th>Table 1. Demographic and Health Characteristics for the OLR and OHR Groups</th>
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Notes: *p < .01, \( p < .1. \)
OLR = old, low-risk fallers; OHR = old, high-risk fallers; SPMSQ = Short Portable Mental State Questionnaire; SD = standard deviation.
any errors made in selecting the appropriate stepping foot included in the response time and any errors made in stepping to the target included in the transfer time. For example, if participants initially raised the incorrect stepping foot and then replaced it before initiating movement with the correct leg, these events increased the response time measure. If participants stepped with the correct leg but did not land on the correct plate and required an additional step to reach the target, this increased the transfer time measure. A high sturdy chair was placed in front of the platform and an assistant stood behind the participant to aid in the event of a possible stumble. However, no participants stumbled or required additional steps to maintain stability after completing the stepping response. The software for recording the events and CSRT times was written in LabView 6.0 (24).

Stepping Obstacle
A low obstacle was included as a test condition to increase the complexity of the motor component of the stepping task. This obstacle comprised a 5 cm high × 2 cm thick Styrofoam block barrier placed immediately in front of and to the sides of the base plates (Figure 1). The blocks were colored a bright blue to ensure that they were clearly distinguishable from the platform. Participants were instructed to step over the blocks in this condition and an obstacle contact score was recorded.

Secondary Task
A “star movement” working memory task was devised based on the Brooks spatial memory task (25). This test was used because it (i) was relatively simple, so the same task could be used across groups and settings, (ii) required participants to use their visuospatial working memory, and (iii) allowed participants to look directly at the stepping plates of the platform while performing the primary stepping task. The star movement task involved participants envisaging three boxes side by side labeled A, B, and C (Figure 2). Participants were then asked to visualize a star located in one of the boxes making three movements. They were told the starting box of the star and the direction of the three movements, i.e., left or right. Subjects were shown a visual display (i.e., similar to Figure 2) during the explanation of the protocol. They then performed sufficient practice without the visual display until they demonstrated that they understood the test requirements and could score 5 consecutive correct responses. For each trial the experimenter verbally delivered the initial position and three movements of the star and immediately following this, a stepping plate was randomly illuminated. Participants completed the step and then reported the finishing box of the star, i.e., box A, B, or C. Performance was recorded in terms of the number of errors made in identifying the finishing position.

Statistical Analysis
Average stepping times were calculated across the four plates for each condition and CSRT component: response time and transfer time. A multivariate analysis of covariance (MANCOVA) was used to examine whether there were differences in response and transfer time as a function of group, working memory task, and presence of the obstacle, adjusting for the variables used to calculate the falls risk score (simple finger-press reaction time, quadriceps strength, edge contrast sensitivity, proprioception, and sway). Where significant interactions were evident, follow-up analyses of variance (ANOVAS) were performed for group (YOUNG, OLR, and OHR) and working memory task (present or absent) on response and transfer times. Kruskal-Wallis tests
RESULTS

Response and transfer times for the YOUNG, OLR, and OHR groups are shown as bar plots in Figure 3. Each bar shows response time (left) and transfer time (right) aligned at the point of commencing the transfer, defined by the appearance of EMG activity. There were significant multivariate main effects of group, working memory task, and obstacle (p < .001 in each case). There was no significant three-way multivariate interaction and one significant two-way multivariate interaction; between group and memory task (Pillai’s trace = 0.115, p < .001). There were significant univariate main effects for group (F_{2,215} = 26.0, p < .001), working memory task (F_{1,215} = 62.7, p < .001), and obstacle (F_{1,215} = 4.3, p = .041, p < .001) on response times and significant group times (F_{2,215} = 22.7, p < .001), working memory (F_{1,215} = 8.6, p = .004), and obstacle (F_{1,215} = 156, p < .001) univariate main effects on transfer times.

Between-group comparisons revealed that the young group had significantly quicker response and transfer times than both older groups (p < .001 in both cases). The OLR group was slower than the OHR group in both response (F_{1,150} = 7.8, p = .006) and transfer times (F_{1,150} = 4.2, p = .043).

There was a significant Working memory × Group interaction for response time (F_{2,215} = 12.6, p < .001) but not transfer time (F_{2,215} = 1.5, p = .22). The working memory task significantly increased response times by 42% in the OLR group (F_{1,70} = 23.4, p < .001) and by 48% in the OLR group (F_{1,86} = 42.5, p < .001) but by only 7.2% in the YOUNG group (F_{1,76} = 2.9, p = .91).

The prevalence of hesitant stepping differed among the groups (Kruskal-Wallis χ^2 = 42.7, df = 2, p < .001). The YOUNG group made fewer incorrect foot lift-offs compared to both older groups (p < .001 in each case). The OHR group made more errors than the OLR group, and this difference reached significance when participants were classified as making 3 or more foot lift-off errors (Pearson’s χ^2 = 4.02, df = 2, p = .045). None of the YOUNG had 3 or more foot lift-off errors compared to 4 (11%) of the OLR group and 13 (30%) of the OHR.

The three groups differed significantly with respect to the number of secondary task errors made (Kruskal-Wallis χ^2 = 19.4, df = 2, p < .001). The YOUNG group made significantly fewer errors than both older groups; three of the YOUNG group (15%) had a combined score of two or more errors in the working memory task conditions compared to 13 (72%) in the OLR and 17 (77%) in the OHR group. A significant difference between the error rates of the OLR and OHR groups was evident (Pearson’s χ^2 = 4.41, df = 2, p < .05) when groups were categorized on a combined score of six or more errors, three of the OLR participants (16.7%) had a combined score of six or more errors compared to nine of OHR participants (40.1%).

The number of obstacle contacts varied significantly among the groups (Kruskal-Wallis χ^2 = 24.5, df = 2, p < .001). Four (25%) of the YOUNG participants had one or more contacts with the obstacle in the two obstacle condition trials compared with 14 (78%) of the OLR group and 20 (91%) of the OHR group. There was a significant difference between the OLR and OHR groups when the groups were classified as making 3 or more contacts with the obstacle; two OLR participants (11.1%) had three or more contacts with the obstacle, compared with 10 OHR participants (45.5%) (χ^2 = 5.56, df = 2, p < .05). In all three groups, the obstacle did not increase the number of secondary task errors, and secondary task did not increase the number of obstacle contacts.

DISCUSSION

Fast response times are critical for successful balance when stepping and walking (27,28). In a previous study we found that CSRT performance was significantly associated with a range of sensorimotor and balance measures including lower limb proprioception, knee extension strength, simple reaction time, and postural sway and that CSRT performance was an important independent discriminator between older people who had and had not fallen (19). CSRT therefore appears to offer a good model for examining the ability of older people to select and execute appropriate balance responses and the attentional demands required for this task.

This study examined stepping time in two components to investigate the contribution of central processing and peripheral neuromuscular and musculoskeletal events. We
found that, across all conditions, the YOUNG group had quicker response and transfer stepping times compared with the OLR and OHR groups: this finding indicates that both central and execution factors show age-related changes.

As hypothesized, a visuospatial working memory task had little effect on response time in the YOUNG group (7% increase), but a substantial effect in the OLR group (42% increase) and more so in the OHR group (48% increase). In contrast, the secondary task produced smaller and proportionally similar increases in transfer times in the three groups. These results indicate that with increasing age and frailty, the secondary working memory task affects the processing time required to activate a correct stepping response to a greater extent than the time to execute the motor command.

An obstacle that made the transfer more difficult produced approximately proportional increases in the transfer times of the young and old participants. The older participants displayed more hesitant stepping as indicated by more incorrect foot lift-offs, made more contacts with the obstacle, and recorded significantly more errors in the secondary task. These results indicate that they had difficulties coordinating the step, negotiating the obstacle, and performing the cognitive task concurrently.

Some previous studies have found that the primary balance task may be prioritized with the addition of a secondary cognitive task (29–1). Brown and colleagues (32) showed that when slowly raising participants higher on a platform, postural stability improved as the postural threat increased, and performance on the secondary task deteriorated. It has been suggested that this deterioration occurs because people who are aware of their risk of falling focus their limited resources to the most important task at hand to minimize information overload and maximize their safety (33). In this study, the OLR and the OHR participants in particular recorded more secondary task errors, possibly not only due to limited attentional resources but also due in part to higher levels of anxiety and fear of falling (29), factors that have been shown to increase the allocation of attention to postural tasks and away from the secondary task (30,31). Importantly, we also found that the primary task—the ability to generate quick, accurate steps in the secondary task conditions—was adversely affected in older people and more so in those with impaired physiological functioning. This finding indicates that these groups are at increased risk of falls as they may be less likely to make a preemptive step in time to avoid tripping when their attention is divided.

The protocol used in the study is particularly applicable to falls that occur through slow or inappropriate visually triggered stepping responses to hazards or unanticipated changes in the gait path. Such responses require anticipatory postural adjustments (34), and it is acknowledged that if this voluntary response is too slow to avoid an obstacle or if there is no visual warning at all, then nonvisual sensory inputs provide the trigger for reflexive perturbation-evoked reactions and the speed of this recovery becomes the important response to maintain balance (35). We chose measures of “correct” response and transfer times as a relevant way of examining functional aspects of stepping speed. By including trials with stepping errors, it is acknowledged that the differences observed among the groups in response and transfer times would have been smaller if these trials were excluded. Finally, although the stepping light was illuminated immediately following the last star movement instruction, and the answer was not given until after the step, it is not possible to determine whether the two tasks were performed simultaneously. Thus the memory task is better described as a secondary rather than a dual task.

**Summary**

We found that across all conditions the YOUNG group had significantly faster response and transfer stepping times than both the OLR and OHR groups and that the OLR group had faster response and transfer times than the OHR group. This finding indicates that, in the generation of a quick, accurate step, both central processing speed in deciding on and initiating the appropriate motor output and movement speed of this command are reduced with age and fall risk. In a secondary task condition, processing time was affected more than movement speed in older people and especially so in those with a high fall risk. Furthermore, errors in performing the secondary task and contacting the obstacle increased with both age and fall risk. These findings suggest that, compared with young people, older people (and more so those at risk of falling) have an impaired ability to initiate and execute quick, accurate voluntary steps, particularly in situations where attention is divided.

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